OCTOBER 1994

--DRAFT WORK PLAN--

EXPERIMENTAL HIGH DISCHARGE RELEASE FROM GLEN CANYON DAM THROUGH GRAND CANYON NATIONAL PARK

Principal Investigator:
Duncan T. Patten
Arizona State University

Co-Principal Investigators:
John C. Schmidt
Utah State University

Edmund D. Andrews
U. S. Geological Survey

Lawrence E. Stevens
Northern Arizona University

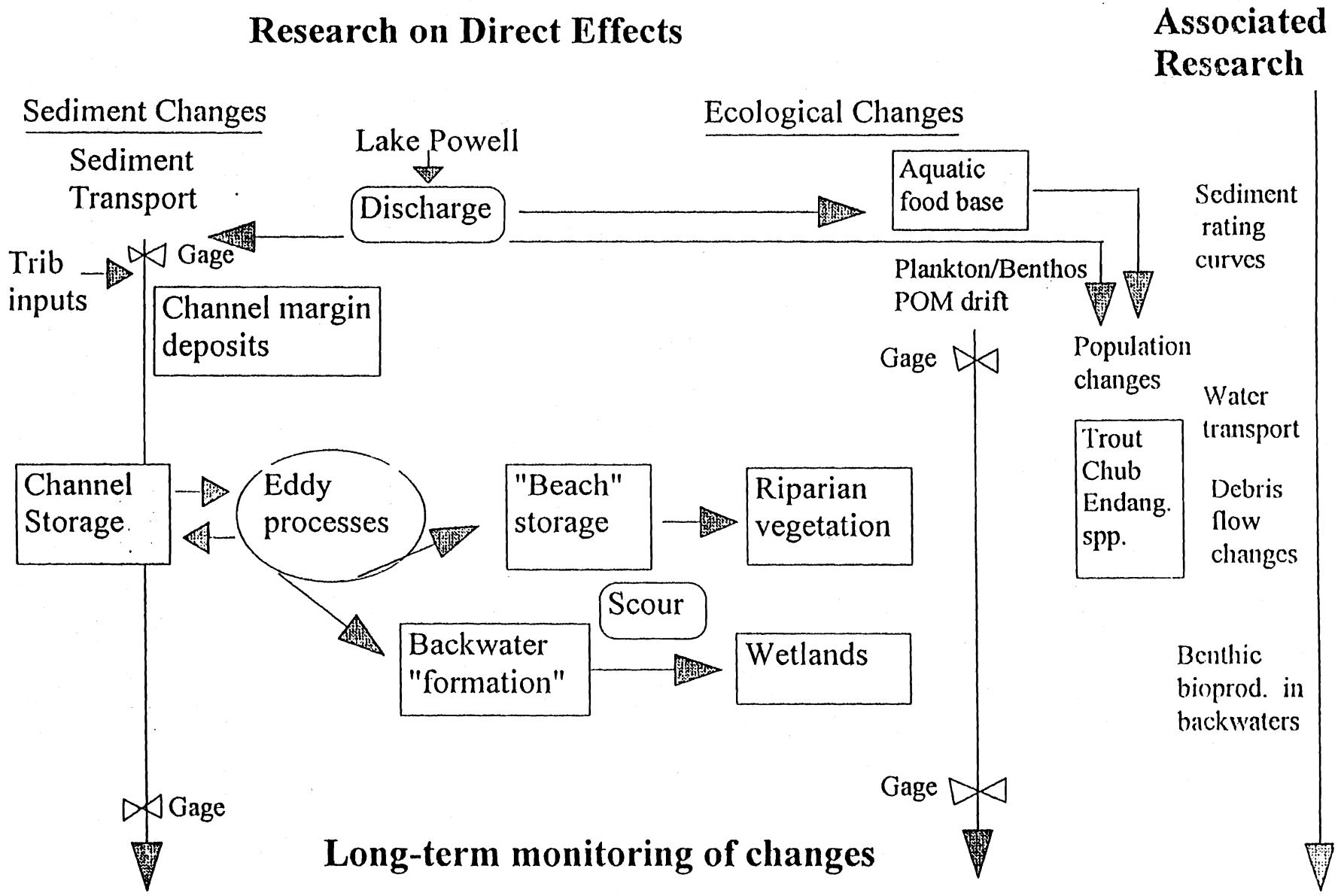
Wendell L. Minckley
Arizona State University

G. Richard Marzolf
U. S. Geological Survey

Jack Stanford
University of Montana

William Jackson
National Park Service

Studies Related to Experimental Flood Event



INTRODUCTION

In spring 1995, an experimental flood is planned for release from Glen Canyon Dam into the Colorado River through Grand Canyon. The purpose of this release is to (1) test the hypothesis that fluvial landforms, aquatic habitats, and terrestrial habitats characteristic of the unregulated Colorado River will be restored by discharges substantially greater than powerplant capacity and (2) provide the opportunity to measure essential geomorphic and ecologic processes during flood passage and flood recession. Results of this experimental discharge will provide information needed to devise an operational flow regime intended to maintain, manage and protect the riparian and aquatic resources of the Colorado River in Grand Canyon National Park.

The planned flood is a part of the culmination of a 10-yr research program funded by the U. S. Bureau of Reclamation's Glen Canyon [Dam] Environmental Studies (GCES) program, and sets the stage for a new phase of adaptive river management described in the recently released draft environmental impact statement for Operations of Glen Canyon Dam (U. S. Bureau of Reclamation, 1994). A substantial body of scientific research has added to our knowledge of processes typical of the unregulated Colorado River in Grand Canyon and changes that have occurred in the river corridor caused by closure of Glen Canyon Dam in 1963. These studies show that the unregulated river environment was dominated by landforms and habitats formed and maintained by high-magnitude floods and that many of these flood-formed attributes have been substantially altered since dam closure. The experimental flood represents a part of a scientifically planned strategy of restoration these habitats.

FLOOD DESIGN

The proposed magnitude of the dam release is over approximately 1,190m^3/s (42,000 ft^3/s). This level of release is about 282 m^3/s (10,000 ft^3/s) above power plant capacity and more than 565 m^3/s (20,000 ft^3/s) above the maximum discharge allowed under Interim Flows. A discharge of this magnitude has not been achieved in the reaches above the Little Colorado River since 1986. The anticipated duration of the high discharge phase of the event will be approximately 7 days. This period is dictated, in part, by availability of water; and is believed to be of sufficient length to produce the geomorphic changes anticipated from this flood experiment and allow for development of tools (e.g., models) for addressing future flood experiments and spills. As presently conceived, the flood will be preceded by 4 days of steady flow at 226 m^3/s (8,000 ft^3/s). The upramp rate to peak flow will be 71 m^3/s (2,500 ft^3/s) per hour and the downramp rate will be 42 m^3/s (1500 ft^3/s) per hour. These ramp rates are not operationally constrained, and have been established based on predictions and measurements of attentuation of discharge waves (S. M. Wiele and J. D. Smith, A one dimensional unsteady model of discharge waves in the Colorado River through the Grand Canyon, unpubl. U. S. Geological Survey manuscript) and to reduce seepage erosion losses (Buhdh, unpubl. ms. 1992). The flood recession will be to 226 m^3/s (8,000 ft^3/s) and held at that steady release for 4 days. Thereafter, normal Interim Flows will resume.

Flood Design Considerations

There are numerous considerations in identifying the desired magnitude of the flood

discharge. The rate of sand accumulation as well as movement of sand within an eddy increase with increasing discharge. Thus, in general, a larger discharge will deposit and form eddy sand bars more quickly than a small discharge. In particular, deposition rate in an eddy depends directly on the concentration of sand in the main channel (Schmidt et al., 1993) which varies by approximately the second to third power of the discharge. Thus, for a fixed volume of water, a larger flood for a shorter duration will likely build larger eddy sand bars. The larger discharge will also deposit sand at higher stages above the levels of normal power-plant release.

For a given volume of water, a larger discharge for a shorter duration will transport more sand out of Grand Canyon and thus deplete a greater volume of the available supply stored on the bed. For this reason, estimates of the quantity of sand stored in the channel will primarily determine how frequently a specific flood can occur. Measurements of the rate of post-flood erosion and vegetation encroachment demonstrate that the high flood attributes of most sand deposits are obscured in less than 7 yrs (Kearsely et al., in press), oftentimes within 1-3 years. The optimum flood magnitude and duration for reestablishment of open,elevated bars should be such that the flood can be generated as frequently as possible without depleting the available supply of sand.

Channel and river characteristics, such as debris-fan height, sand storage, and projected sand-transport load, affect determination of the optimum flood magnitude, duration, and frequency. One factor or another may be especially important at a given location. As described above, areas of separated flow are extinguished when river stage exceeds the top of the debris fan that causes a channel constriction. When areas of separated flow are extinguished, most if not all of the sand stored in the eddy is lost downstream. Consequently, the desired flood stage should be less than the height of debris fans located in critical reaches where campsite availability is limited (Kearsely et al., in press). Melis (T. S. Melis, hydrologist, 1993, U. S. Geological Survey, Tucson, written commun.) has shown that these critical reaches are characterized by low-elevation debris fans. The optimization of flood magnitude, duration, and frequency thus will ultimately be related to the general characteristics of critical reaches targeted for management. Presently, the characteristics of upper Marble Canyon seem to be most appropriate for detailed flood design.

The proposed flood magnitude and duration are estimated based primarily on observations made at discharges less than power-plant capacity, plus some data collected between 1983 and 1986. It would be fortuitous if the proposed experimental flood was, in fact, optimum. Accordingly, purposes are three-fold. First, to evaluate effects of this specific event. Second, and perhaps most importantly, to gain a quantitative description and understanding of the essential processes controlling (1) transport of sand in the main channel and (2) the temporary storage of sand in eddies and development and/or maintenance of return channels (often called backwaters for biological purposes). A detailed understanding of these processes will provide information needed to predict water and sediment flow through Glen, Marble and Grand Canyons and the rate of sand deposition in eddies at discharges not specifically measured, in addition to effects on riverine ecosystems. These support the third purpose which is to develop tools for more accurate evaluation and management of future spills.

Whatever the outcome of this one experiment, we do not anticipate that there will be a single optimum flood proposed for management of the whole Grand Canyon. Rather, the

optimum flood magnitude and duration for building sand bars and forming backwaters will vary from year to year and reach to reach depending also on availability of water in Lake Powell reservoir and the supply of sand on the river bed. Designing flood magnitude and duration for river conditions of a specific year instead of for the long-term average condition will necessarily require some sophisticated long-term computational methods along with simpler sediment budget calculations including monitoring of the status of sand stored within the river reaches. Evaluation of other riverine resources will also necessarily be part of future flood designs.

OVERVIEW

The central premise of the experiment is that (1) floods are essential fluvial processes necessary to maintain the Colorado River's pre-dam geomorphic character, and (2) the river's geomorphic character and associated processes influence aquatic and riparian ecology. Geomorphic components include sandbar morphology, eddy sediment storage, and mainstem sediment transport and storage, while ecosystem components that may respond to geomorphic changes include benthic communities, indigenous and non-indigenous fishes, and riparian and marsh vegetation. Sand bars deposited in zones of low velocity along channel margins are features of special interest. These deposits are used as campsites by river runners, form backwater aquatic habitats that may be required by indigenous fish, and serve as substrate for riparian vegetation established following dam closure.

Sand bars deposited in areas of flow separation along channel margins are common geomorphic features of a wide variety of rivers, by no means unique to the Colorado. However, height and steepness of walls and narrowness of the canyon are such that flow separation and eddy-related sedimentation are unusually well-developed in Grand Canyon. An unusually high proportion of sand bars form within these eddies, and the bars are essential recreational and ecological resources.

The principal scientific questions to be addressed by the flood experiment relate to the optimum flood magnitude, duration, and frequency necessary for rejuvenating or rebuilding sand bars and associated backwater-sand bar aquatic and terrestrial habitats in Grand Canyon. There is a clear need to seek the optimum flood magnitude and frequency because such a staged event entails substantial resource cost, primarily a loss of electric power generation due to loss of the volume of water released in excess of power-plant capacity and a loss of a proportion of sand stored in the main channel through transport into Lake Mead reservoir.

General Working Hypothesis

The null hypothesis to be tested by this dam release is that *the magnitude and duration of this flood will have no long-term effect on the Grand Canyon riverine ecosystem as a whole.* The alternative hypothesis is that *the magnitude and duration of the flood will result in measurable and predictable changes in the river geomorphology and thus the aquatic and riparian ecosystem.*

Awareness of Ecological Risk: Development of an experiment to test these hypotheses produces some risk for ecological resources involved. Although not a reason to curtail the

research, this risk requires awareness of possible consequences of the experimental process. The planned high flow experiment may produce unknown effects. These include: (1) the impacts on the sediment-depleted reach from Glen Canyon Dam to the Paria River; (2)the availability of sand in narrow reaches of Marble Canyon to which will be delivered to eddies; (3) the capability of the flood to open and regenerating return current channels and backwaters; (4) the extent of loss of wetland and riparian vegetation, and associated terrestrial habitat; and (5) the direct and indirect impacts on endangered species and their habitats, and on riverside cultural resources. At present, a scientific consensus exists that likely benefits from this event will outweigh potential losses and that the uncertainties represent acceptable risk.

SCIENTIFIC BACKGROUND

Geomorphology: the unregulated river

The Colorado River through Grand Canyon is a gravel-bedded stream that primarily transports sand and finer sizes as suspended load. The width of the Colorado River is constrained by bedrock, talus, or debris fan deposits throughout most of its 425-km course between Glen Canyon Dam and Lake Mead reservoir (Howard and Dolan, 1981). Debris fans, composed of coarse material supplied from steep ephemeral tributaries, partially block the channel's course at more than 165 rapids. Channel constrictions result and often form these rapids, for which the Colorado River is famous.

There is a distinctive assemblage of channel elements related to point source contributions of coarse material to the river. A backwater of low-velocity flow may extend several kilometers upstream from the debris fan (Kieffer, 1985). Downstream from the debris fan, channel cross-section area increases, and large recirculating eddies occur along the channel banks in these expansions. The downstream termination of these eddies is typically caused by flow acceleration due to water passage over or around a cobble/gravel bar, narrowing of the constraining bedrock or talus banks, or where the main channel flow impinges on curving channel banks. This geomorphic configuration occurs at every tributary mouth, and the size of each channel element is related to the size and characteristics of each debris fan, the time sequence of debris flows that replenish the fan, and the time sequence of Colorado River discharges. Other sources of coarse materials include the channel margin deposits that are not associated with debris fans and eddies.

Many of the managed resources of Grand Canyon National Park are geomorphically based and are part of the assemblage described above. Early photographs of Grand Canyon show that much of the river corridor was comprised of bedrock, talus, debris flow deposits, and bare sand bars; perennial riparian vegetation primarily existed as linear strips on terraces above about the 2820 m^3/s (100,000 ft^3/s) stage, on higher terraces that existed in some locations, and on the high parts of debris fans. Open sand bars were a distinctive geomorphic feature of the unregulated river corridor.

Prior to closure of Glen Canyon Dam, the Colorado River varied greatly in discharge throughout the year. Between 1 September and 1 March, mean daily discharge was about 141 m^3/s (5000 ft^3/s), but instantaneous peak discharges frequently exceeded 1410 m^3/s (50,000 ft^3/s) in September and October. The annual peak discharge was caused by snowmelt and occurred, on average on June 5. The mean annual peak flow for the period 1921 to 1962 was 2180 m^3/s

(77,500 ft^3/s), as measured at Phantom Ranch, and the mean daily discharge for the same period was about 478 m^3/s (16,900 ft^3/s). In 50 percent of all years between 1922 and 1962, discharges of at least 1410 m^3/s (50,000 ft^3/s) were sustained for about 30 days.

Sediment transport also varied greatly throughout the year. The average annual sediment load of the Colorado River at Lees Ferry was about 6.0×10^{10} kg (Andrews, 1991). At the Phantom Ranch gage, located approximately 170 km downstream from Glen Canyon Dam, the mean annual sediment load for the same period was about 7.8×10^{10} kg per year, indicating that about 1.8×10^{10} kg were contributed by tributaries. Andrews (1990) estimated that about 70 percent of this amount was contributed by the Paria and Little Colorado rivers. The quantity of transported sediment is small for such a highly turbulent river that transports such fine sediment. Sediment coarser than 0.5 mm comprised less than 1 percent of the pre-dam measured sediment load (Smith et al., 1960)

Availability and equilibrium of sand on the bed of the river have, at times, been estimated. Wilson's (1986) side-scan sonar surveys, as summarized by the U. S. Department of the Interior (1988, table A-2), indicate that stream bed composed of bedrock or boulders varied between 30 and 81 percent during three surveys in 1984, possibly indicating bed sand amounts between 70 and 19 percent. Sediment-transport modeling (S. M. Wiele and J. D. Smith, A one-dimensional unsteady model of discharge waves in the Colorado River through the Grand Canyon, unpubl. U. S. Geological Survey manuscript) indicates that less than 50 percent of the bed need be covered with sand to maintain equilibrium transport through Grand Canyon. Video imagery and side-scan surveys since 1990 indicate that large portions of the bed are composed of gravel and cobbles (J. D. Smith, hydrologist, U. S. Geological Survey, Boulder, pers. commun., 1994).

Areas of separated flow (eddies) have low velocity and turbulence. Accordingly, eddies are prominent sites of sediment accumulation. Sand bars deposited in zones of flow separation have distinctive topography and location relative to this flow geometry. Schmidt (1990) classified lateral flow-separation eddy bars as *separation bars* formed near the flow-separation point and which mantle the downstream parts of debris fans and *reattachment bars* that form under the primary recirculating eddy cell. *Channel-margin deposits* are those which occur as narrow floodplain-like strips throughout the river corridor.

Eddy bars persist in specific zones of recirculation because channel obstructions that give rise to flow separation rarely change. Although bars change shape with discharge, they remain within specific lateral separation eddies and do not migrate from eddy to eddy. Measurements, observations and rematching of historic photos of the Colorado River in Grand Canyon (Turner and Kapisak 198, Howard and Dolan,1981; Schmidt and Graf,1990) show that the locations of some eddy sand bars have been stationary during the past century, and observations on the relation between flow geometry and sand-bar location suggest that bars should be persistent over periods consistent with the frequency of events that substantially reshape flow-separation-inducing obstructions (Rubin and others, 1990; Schmidt, 1990). In Grand Canyon, that time scale is on the order of 10 to 100 yrs (Webbet al., 1989).

Large floods may overtop debris fans and cause recirculation zones to diminish greatly in size or disappear (e.g. Kieffer and others, 1989, fig. 3.5). Melis (U. S. Geological Survey, hydrologist, Tucson, written commun., 1993) has shown that most debris fans are overtopped by

discharges at or greater than the pre-dam mean annual flood, and photographs and observations of the river at discharges near 2830 m^3/s (100,000 ft^3/s) show that many eddies are thin or non-existent at that discharge. Because eddy deposits are composed of sedimentary structures indicative of recirculation (Rubin and others, 1990, 1992), eddy bars are formed by flows less than the magnitudes that drown the controlling constriction. Thus, fine-grain river deposits must form at discharges less than those that overtop fans or, during the descending limb of a flood hydrograph. The characteristics of eddy deposits prior to closure of Glen Canyon Dam should therefore have reflected characteristics of sediment transported during recession from the annual spring peak and features of lower-magnitude late-summer flood flows.

Eddy bars are subject to scour and fill over various time scales. Interpretation of sedimentary structures and recovery of scour chains (Rubin and others, 1990, 1992) show that eddy bars are dynamic features, subject to erosion and deposition during floods. Erosion also occurs after flood recession but some bars demonstrate greater stability than others and may go through erosion and deposition cycles within the limits of the river stage. The topographic form and internal stratigraphy of bars results from the range of eddy geometries that occur at each site, which are dependent on channel geometry and discharge (Rubin et al., 1990). Eddy bars associated with low debris fans that are overtopped frequently by mainstem flooding are likely to have different scour-and-fill histories than eddy bars in the lee of high-elevation debris fans that are overtopped less frequently.

The topography of reattachment bars results, at low flow, in a deep channel of stagnant flow adjacent to the shore and blocked from the main current by the emergent bar. These stagnant-flow areas increase in nutrient and other concentrations, productivity and biota due relative to the river due to increased temperature and deposition of silts and clays, hyporheic percolation through the bars, solar radiation, and greater time of occupancy by water. Backwater areas are thus potentially important as a rearing habitat for native fishes. However, the magnitude and duration of flows required to initiate opening of return channles are poorly understood

Geomorphology: the regulated river

Closure of Glen Canyon Dam caused a substantial reduction in volume and a change in the pattern of occurrence of the mean annual flood, and in the volume and pattern of sediment entering Grand Canyon. The post-dam 2-yr recurrence flood at Lees Ferry is 795 m^3/s (28,100 ft^3/s) for the period 1963 to 1993 but the distribution of post-dam high annual peaks, with few exceptions, has been tied more to water management at Glen Canyon Dam than stochastic events. Water release can be subdivided into "normal" years when less than 1.2×10^{10} m^3 of water are released and annual peak discharges are less than powerplant capacity, and "high" years when flows 2 or 3 times greater than powerplant capacity occur. Such high-release years have only occurred in 1965, 1980 and between 1983 and 1986. Ranges of fluctuations associated with daily production of hydroelectricity is dependent on the annual and monthly volume of released water. Generally, flows have not fluctuated in high-release years but have fluctuated as much as 793 m^3/s (28,000 ft^3/s) per day in normal-release years (U. S. Bureau of Reclamation, 1994, fig. 11-5).

Randle et al. (1993) computed annual sediment budgets for each year between 1966 and

1989 for the 141-km reach between Lees Ferry and the Colorado River gaging station near Grand Canyon (number 09402500), using hourly discharge data and average sediment transport relations for the gaging stations that constitute sediment inputs to this reach (Lees Ferry, Paria and Little Colorado rivers: stations 09380000,09382000, and 09402000) and the one gage that is the sediment output (Grand Canyon: 09402500). They also computed budgets for the subreaches upstream and downstream from mainstem station 09383100, located just upstream from the Little Colorado River. Their results, consistent with analyses by Howard and Dolan (1981), indicate that the probability of accumulating sediment in themain channel over extended periods (80 years) of alternive sequences of mainstem hydrology and tributary inputs varies from about 30-80%, depending upon how discharges from Glen Canyon Dam are managed. Although net degradation of accumulated sediment occurred between 1983 and 1986 during high release years, under an interim flow regime there is a 70% probability that sediment storage in the main channel will increase over 80-year time periods..

Predictions about long-term change of alluvial bars in Grand Canyon have differed. Although Dolan and others (1974) suggested that widespread erosion of sediment deposits might result from dam operations and Laursen and others (1976) estimated that there was a large deficit in the regulated sediment budget for Grand Canyon, Howard and Dolan (1981) found that sediment deposits had "suffered only a very slight net erosion" after dam closure. Several studies measured patterns of aggradation and degradation associated with the high annual peak discharges that occurred between 1983 and 1986 (Beus et al., 1985; Schmidt and Graf, 1990). On-going sand-bar monitoring (S. S. Beus and C. C. Avery, eds., The influence of variable discharge regimes on Colorado River sand bars below Glen Canyon Dam, unpubl. consultants' report to Grand Canyon National Park) indicates that rates of sand-bar erosion decline with time following major floods and that there are many sedimentation processes that restore sediment to formerly eroded sites. Schmidt and others (J. C. Schmidt, R. H. Webb, and P. E. Grams,1994, Using inventory techniques to assess geomorphic change in eddy-dominated rivers, unpubl. manuscript) demonstrated that reattachment bars and channel-margin deposits are more susceptible to erosion than are separation bars.

Changes in campsite availability reflect changes in large, high-elevation sand bars. Kearsley et al. (in press) have shown that at least 30 percent of all campsites decreased in size between 1963 and 1973. During the next 18 yrs, between 1973 and 1991, 32 percent of all campsites decreased in size, and campsite capacity decreased by 44 percent. Although high discharges in 1983 caused aggradation at a number of sand bars, by 1991 almost allthese sites had eroded to pre-1983 conditions.

Results from sand-bar resurveys, campsite inventories, and computations of sediment mass balance demonstrate that sediment has accumulated on the channel bed while upper surfaces of sand bars have eroded during periods of normal powerplant operation (1965-1979, 1986-1994) when discharges do not exceed power-plant capacity. Entrainment of accumulated sediment on the channel bed and transfer of this sediment to channel margins occurs when flows exceed powerplant capacity and when there is sufficient sand stored on the channel bed. Transfer of sand from the channel bed to the banks is one of the major objectives of flood management.

Ecology

Riparian Ecosystem

The ecology of the Colorado River corridor was transformed by closure of Glen Canyon Dam. Carothers et al. (1979) discussed zonation of Grand Canyon's riparian vegetation. These observations were further clarified by Turner and Karpiscak's (1980) rematching of historic photographs throughout the Colorado River riparian corridor. Johnson (1991) summarized trends in post-dam vegetation change in this system, and Stevens and Ayers (L. E. Stevens and T. J. Ayers, 1993. The impacts of Glen Canyon Dam on riparian vegetation and soil stability in the Colorado River corridor, Grand Canyon, Arizona, unpubl. report to Grand Canyon National Park) reported on the results of test flows under the GCES Phase II program. Recruitment in the old-high-water-zone (OHWZ) community has declined due to the decreased frequency of large magnitude floods. This zone, the only perennial riparian vegetation community of the unregulated river, was watered by sporadic flood-flows; the assemblage was adapted to drought and rare, high floods.

Lower riparian zone vegetation is now dense and is composed of different species than the upper riparian OHWZ community. Saltcedar and sandbar willow have colonized many bars down to a stage associated with a discharge of 300 m^3/s. Marsh assemblages, formerly rare to absent in this system, have colonized patches of silt- and clay-rich alluvial sediments near the elevation of mean baseflow in backwater return-current channels. Vegetation encroachment, daily stage fluctuations related to hydroelectric peak power production, and in-filling by slope processes tend to obscure sand bar and backwater topography typical of the unregulated river.

Under reduced levels of flow fluctuation and ramping rates of the current Interim Flows, macrophytic vegetation has rapidly colonized newly stabilized, low-elevation deposits of the Colorado River corridor (L. E. Stevens and T. J. Ayers, 1993, The impacts of Glen Canyon Dam on riparian vegetation and soil stability in the Colorado River corridor, Grand Canyon, Arizona, unpubl. report to Grand Canyon National Park). At nearly every site examined, Stevens and Ayers reported that the "new dry" zone at water stages between discharges of 566 and 890 m^3/s sustained a surprising amount of primary colonization by emergent herb, macrophytic, and clonal perennial vegetation. However, these researchers noticed die-back of sandbar willow ramets attributable to desiccation of higher surfaces inundated by stages associated with discharges of about 1100 m^3/s at two study sites. Premature chlorosis of this marsh-indicator species was noted at one other site. High discharges of the Little Colorado River in winter 1993 scoured large areas of low-lying vegetation and aggraded backwater channels.

Aquatic Ecosystem

The change in characteristics of the Colorado River below Glen Canyon Dam has fundamentally altered the aquatic food base. The overriding factors influencing these alterations are dam operations which create clear, cold water, and turbidity from tributaries which result in a gradual decrease in benthic standing biomass below the confluence of the Paria River. The filamentous green alga, *Cladophora glomerata*, dominates the benthic community between the dam and Paria River because of the clarity of the water and substrate availability, while *Oscillatoria* spp., crustose bluegreen algae (cyanobacteria) dominates downstream of the Little Colorado River. Standing biomass and abundance of other benthic organisms is closely

correlated with the presence of *Cladophora* and therefore declines with distance from the dam. Because *Cladophora* serves as a substrate for epiphytic diatoms which composes the major portion of the diet of the aquatic chironomid dipterans, and the introduced, non-indigenous amphipod, *Gammarus lacustris*, populations of these taxa have increased in the aquatic environment of the Canyon following closure of the dam.

Changes in physical characteristics of the river have also altered the fish assemblage. The clear, cold tailwater between the dam and Paria River, and establishment of a productive food base in this reach, have permitted development of a population of non-idigenous trout, managed to maintain a recreational fishery. Cold water, coupled with existence of an exotic predatory fish have led to essential extirpation of the original eight indigenous Colorado River fish species between Glen Canyon Dam and Lake Mead (Minckley 1991). Of the original indigenous species, humpback chub, bonytail, Colorado River squawfish and razorback sucker are listed as endangered (bonytail and squawfish are locally extirpated), while speckled dace, flannelmouth sucker, and bluehead sucker remain relatively common. Of the endangered fishes, only humpback chub maintains a reproducing population, an apparent result of its use of the Little Colorado River as a refuge and spawning site.

Studies during Phases I and II of the Glen Canyon Environmental Studies have demonstrated that geomorphological changes in concert with hydrological changes and alteration of water physical features (e.g., temperature and sediment transport) have altered many of the ecological processes within the Colorado River riverine system below Glen Canyon Dam. Periodic reestablishment of the geomorphic and hydraulic processes that may enhance maintainence of ecological processes and communities without creating negative effects on existing biota, especially indigenus species, should be another of the major objectives of flood management, in addition to sand transfer from channel bed to banks.

EXPERIMENTAL DESIGN

GEOMORPHOLOGY

Objectives

The objectives of this part of the study are to validate predictions of (1) locations and rates of sand deposition along margins of the channel, (2) locations and magnitude of net erosion, and (3) characteristics of water and sediment transport in the main channel, and eddies and return current channels. Measurements will focus on quantification of the rates of geomorphic processes, descriptions of these processes, mapping of existing deposits, and measurements of flood-formed deposits. Measurements will also be made of the rate of post-flood adjustment of newly formed deposits.

Justification

As described above, use of intentional floods as a tool in habitat reconstruction depends on (1) accurate understanding of the sediment budget, (2) ability to predict reach-averaged rates of channel-margin deposition, and (3) determination of variance of the spatial pattern of reach

deposition. In addition, prediction of geomorphic effects of floods over a range of discharges will come by an appropriate synthesis of modelling and field studies. Prior to this flood experiment, models using controlled high flow data have been limited to 790 m^3/s (28,000 ft^3/m). Some basic data with which to further calibrate models can be obtained during this experimental flood. Geomorphic data will also we used in understanding the processes that cause habitat changes for aquatic and riparian species, for example, development of return current channels (backwaters).

Hypotheses

The following hypotheses will be tested by performing the experimental flood:

Spatial Patterns of Bar Deposition

Null hypothesis--

H0: There will be no net change in the number, size, shape, or location of channel-margin alluvial deposits 1 yr after recession from this flood.

Alternative hypotheses --

H1: Following the flood, reattachment bars will resemble those described by Schmidt and Graf (1990) as existing in Grand Canyon in the mid-1980's. Well defined eddy return current channels will exist and their number and size will exceed the number and size of such channels as they existed prior to the flood.

H2: There will be a net increase in the total number and size of alluvial deposits along the river.

The above mentioned alternate hypotheses are only general statements. Each alternative could also be restated by individual subreach and for other measurement periods (e.g. 1 month after the flood, 6 months, 2 yr, etc.)

Main channel hydraulics and sediment transport

Null hypothesis--

H0: Sediment mass balance calculations and global models of hydraulics and sediment transport successfully predict high discharge sediment transport. Eddy deposition calculations and numerical modeling of eddy circulation successfully predict eddy deposition rates.

Alternative hypotheses--

H1: Modeling does not predict river hydraulics and sediment transport. Eddy deposition rates are not accurately predicted.

Methodology

The general method of this research will combine specific field measurements at numerous field sites (e.g., gaging stations, long-term sand-bar survey sites, sites of recent debris flows) with comprehensive river-length analysis of air photography. The scale of the river and length of Grand Canyon preclude intensive study of all potential deposition sites. Field

measurements during the flood will not only be analyzed to test hypotheses but also to refine and improve models of river hydraulics and sediment transport.

1. a. Spatial Patterns of Bar Deposition – reach scale

The purpose of this effort is to quantify the areal extent of newly formed bar deposits and measure bar adjustment following flood recession. These data will be used to test hypotheses regarding net change in bar area caused by the flood. Methods will be similar to those used by Schmidt (J. C. Schmidt et al., 1994. Geomorphology of post-Glen Canyon Dam fine-grained alluvial deposits of the Colorado River near Point Hansbrough and Saddle Canyon in Grand Canyon National Park, Arizona, unpubl. report to GCES) in which surficial river-corridor geology, based in part on aerial photographs, is mapped at 1:2400 scale on base maps that depict the river corridor in June 1990. Schmidt's maps also depict the status of sand bars depicted on photographs taken in 1935, 1965, 1973, 1984, and 1990. Clark (1990) completed maps of surficial geology for the reach near Nankoweap Creek for 4 additional years (1980, 1987, 1988, 1989). These maps are useful in predicting the elevation of the water surface and zones of bar deposition at discharges comparable to the magnitude proposed here.

In order to evaluate the areal extent of deposition due to the planned flood, similar maps will be made for selected reaches (initially in the established GIS reaches) based on interpretation of aerial photos and field work (1) at low flow immediately prior to the flood, (2) at low flow immediately following flood recession, and (3) at selected times that photos are taken each year following flood recession. Maps made as part of this experiment will be entered into the GCES GIS (Geographic Information System) data base and compared with predictions.

1. b. Spatial Patterns of Bar Deposition – site-specific scale

Detailed patterns of bar deposition, and characteristics of bar deposits will be determined from resurvey of geo-referenced topographic maps of 30 field sites. These sites have been surveyed annually by the GCES program and are all part of the GCES GIS data base. Using established protocols, detailed topographic surveys will be conducted immediately prior to and after the flood. Comparisons of topographic change will be made using techniques established by Beus and others (S. S. Beus et al., 1993. The influence of variable discharge regimes on Colorado River sand bars below Glen Canyon Dam, unpubl. report to Grand Canyon National Park). Sedimentologic excavations and examinations will also be made at the survey sites to test depositional sequences predictions for those locations.

These data will be used to evaluate detailed spatial characteristics of eddy deposition and determine the volume of sediment deposited in specific eddies. These data will be used in conjunction with areal determinations of the extent of new deposits to estimate a reach-average volume of newly deposited sediment.

2. a. Main channel hydraulics and sediment transport

The primary data to be collected concerning the main channel are (1) velocity and sediment concentration at 4 gaging stations (Lees Ferry, above the Little Colorado River, Grand Canyon and Diamond Creek), (2) time of water travel based on measurements of dye concentration, and (3) documentation of bed-sand-storage changes. Time-of-travel studies are

essential for further refinement of the global model of water flow (S. M. Wiele and J. D. Smith, A one- ~3 dimensional unsteady model of discharge waves in the Colorado River through the Grand Canyon, unpubl. U. S. Geological Survey manuscript). No determinations of bed roughness have been made at high discharge (greater than 620 m^3/s) and such a roughness parameter is necessary to accurately predict water surface elevations, wave attenuation, and sediment transport.

Basic velocity and sediment transport data at gaging stations will provide essential empirical data to be used in refining sediment rating curves, in calculating sediment budgets within reaches, and in comparing model predictions of sediment transport actual values. Predictions of the concentrations of suspended sediment and total transported load during the flood will be compared with data collected during the flood.

2. b. Eddy hydraulics and sediment transport

The mechanics of flow circulation and sediment transport will be studied in detail at 5 to 7 eddies. Daily measurements will describe the net gain or loss of sediment during the preceding day, changes in topography of the separation and reattachment bar and return current channel, exchange rate of water between main channel and the eddy, and concentration of suspended sediment in the main channel adjacent to the eddy. The surface-velocity field of the eddy will be measured at least daily during the flood. Measurements will be analyzed to determine the rate of sediment deposition over duration of the flood, adjustment of eddy bar topography, and variations in mass-exchange rate as the eddy bar approaches its equilibrium configuration given the discharge and suspended sand concentration in the main channel. The observed evolution of bar topography will be used to evaluate a vertically averaged two-dimensional model of eddy circulation.

ECOLOGY

Geomorphological processes control most of the development of appropriate habitat for wetland (marsh) and riparian species. Changes in the status of return current channels (backwaters) that may fill with sediment allow establishment of marsh plants, but continued filling will gradually raise the substrate levels and eliminate conditions suitable for these plants. A clearer understanding of the circulation processes in eddies before and during high flows will guide our understanding of how sediment transport processes cause the formation and loss of locations that become marshes and will allow testing of predictions on rates of scour and filling, marsh habitat creation and loss, and marsh ecosystem evolution.

Sediment deposits that support riparian vegetation also change constantly as a result of variations in river discharge. Although riparian vegetation may help stabilize sediment deposits, the energy of river flows is sufficient to alter substrate under riparian plants, often causing loss of riparian communities. Sediment deposition processes also create new habitat for riparian species. This along with limited post-dam discharges have allowed an extensive invasion of previously scoured areas by both indigenous and non-indigenous riparian species. The interrelationships between sediment transport and depositional processes, and riparian and

marsh ecosystem processes makes it essential to conduct studies of the influence of flood flows on riparian and marsh communities and backwater ecology in close concert with geomorphological studies. Coordination of geomorphological and ecological studies will include both timing and location.

Wetland and Riparian Vegetation

Objectives

The objectives of this part of the study are to monitor and, where possible, model the impacts of planned flooding and changes in geomorphology on wetland and riparian vegetation area, patch distribution, cover and composition, and processes of vegetation loss and recovery. We anticipate a planned high-flow experimental release from Glen Canyon Dam will have predictable, minor and short-term impacts on the existing dynamic condition of wetland and riparian vegetation. Loss of wetland and riparian vegetation to scour will be a function of stage, geomorphic location, and life-history strategy (specifically root architecture). Site stability will be positively correlated with above-ground cover, stem density and root density, negatively correlated with velocity, and will be non-linearly, negatively correlated with the size of reach deposited sediment in various geomorphic settings. Recovery of vegetation will be a function of life history strategy (vegetative versus seed-based reproduction), stage and geomorphic location. We expect Colorado River streamside vegetation will rapidly redevelop following the experimental flood.

Justification

Flooding is an essential, ubiquitous and natural process in fluvial ecosytems. As a form of disturbance, flooding alters landforms by scouring and reworking sediments, and killing or damaging established riparian vegetation (White 1979, Sousa 1984, Pickett and White 1985, Stevens and Waring 1985). These changes exert direct and indirect impacts on fluvial sediments, processes, and aquatic and wetland/riparian assemblages (Ponamperuma 1984, Kozlowski 1984, Petts 1984, Stevens and Waring 1985, Gore and Petts 1989, Schmidt and Graf 1990). Overall, flooding effects on riparian plant assemblages are predicted to increase with increased flooding intensity (sensu Connell 1978), and therefore with the magnitude of discharge.

The diversity of sessile organisms, such as wetland and riparian plant species, are influenced by interactions between disturbance (Connell 1978) and productivity gradients that interact with life-history parameters (Huston 1979, 1994). Stevens and Waring (1985) and Stevens (1989) examined flood-related distribution of riparian vegetation in the Colorado River and its tributaries in Grand Canyon. From studies of the 1983 high flows, they showed that flood-related mortality differed markedly between riparian plant species on the basis of architecture and growth strategies. Mortality of shallow-rooted taxa in fine-grained environments was attributed to scour, while deeply rooted taxa in debris fan environments perished through drowning. Clonal woody species suffered extensive ramet mortality, but considerably less genet loss, as compared to all other wetland and riparian species.

Productivity is strongly correlated with moisture availability in arid-land riparian

environments, and is closely related to flood-related disturbances. Stevens and Ayers (1993) concluded that wetland vegetation sites floored with silty soils change rapidly from an annual *Gnaphalium chilense/Aster subulatus* association in the first year, to clonal *Typha/Phragmites* association in silt-rich, high-inundation sites, or to woody *Tamarix/Salix* association in sandy, low-inundation sites. The direction of the successional processes following a flooding event will thus be highly dependent on scour and depositional patterns, and local velocities during the flooding.

Hypotheses

The planned flood flow from Glen Canyon Dam is expected to alter the existing dynamic condition of wetland and riparian vegetation downstream Colorado River fluvial ecosystem. The following hypotheses will be tested by this experiment.

Null hypothesis 1--

HO 1: A planned flood flow from Glen Canyon Dam will not alter the existing dynamic relationships between riverine geomorphology and wetland and riparian vegetation downstream Colorado River fluvial ecosystem.

Secondary-Null hypotheses--

HO 1a: System-wide reach geomorphology will not influence wetland and riparian vegetation area, patch distribution, structure, composition, or standing crop.

HO 1b: Geomorphologic attributes of specific sites will not interact influence wetland and riparian vegetation area, patch distribution, structure, composition, or standing crop.

Alternative hypothesis--

H 1: Wetland and riparian vegetation will be significantly altered by the flood flow; however, recovery of wetland vegetation will proceed rapidly as a function of extent of scour, inundation frequency, grain size, microsite slope, and propagule availability.

Null hypothesis 2--

HO2: A planned flood in early spring will not result in significant increases in non-native plant populations in the Colorado River riparian corridor.

Alternative hypothesis--

H2: The timing of the flooding event will encourage the establishment of non-native wetland and riparian plant species along the Colorado River corridor.

Methods

This experimental program will investigate three components of flooding effects on riparian/wetland vegetation: (1) before and after surveys of system-wide effects; (2) observation and measurement of flood-related scour of riparian vegetation at sand-bar sites; and (3) model

refinement and experimental testing of trajectories of vegetation recovery at a single site. The methods used in this effort include: (1) evaluation of flood effects through on-going monitoring before and after the flooding event; and (2) detailed studies at locations coordinated with geomorphological studies for testing specific hypotheses relating sediment changes and riparian/wetland responses to be conducted before, during and after the flood event. Studies of long-term recovery of riparian/wetland vegetation, as with long-term geomorphological changes, will be part of a future long-term monitoring program.

Secondary Null-hypothesis 1a:

Wetland/riparian vegetation research in the Grand Canyon has focused on variation in basal area and composition across soil, moisture availability and flood-related disturbance gradients in several distinct geomorphic settings (Stevens and Ayers 1992, 1993, 1994). Fluvial marshes have been monitored through analysis of aerial photographs since 1965, and in the field on an annual basis since 1990 (Stevens et al. in press). Monitoring should be conducted prior to and after the flooding event using the following methods:

1) A series of 50 permanent 1.0 m^2 georeferenced quadrats has been established at 12 sandbar marshes. These quadrats will be monitored in the autumn before the high flow and in the spring immediately after the high flow. Future annual monitoring, if appropriate, will be part of the long-term monitoring program. Stage-related elevation, grain size, species composition, basal area, dead stem density and reproductive output will be monitored. Comparable plots in tributaries will be monitored to provide off-river controls. A series of 0.1 m^2 standing crop plots will be monitored before and after the flooding event and compared with previously collected data to provide an assessment of standing crop changes associated with flooding.

2) Measurement of 20 new-high-water-zone (NHWZ) marshes and four OHWZ spring marshes will be continued using the GCES Map and Image Processing System (MIPS). The NHWZ marshes were distributed throughout the river corridor, and were selected by Stevens and Ayers (1993) on the basis of distribution within geomorphic reaches established by Schmidt and Graft (1990). The four OHWZ marshes constituted a set of control sites against which to determine changes in wetland vegetation not induced by dam operations. These marshes have been measured on 1988, 1990, 1991, 1992 and 1993 photographs and will be remeasured on aerial photographs taken before and after the flooding event.

3) Twenty study areas have been established in Glen, Marble and Grand Canyons and provide an adequate baseline under which to measure system-wide effects of planned flooding. Each contains 5 m x 10 m permanent quadrats in the following geomorphic environments: marsh, beach (sand bar platform), channel margin and debris fan habitats, as well as in the OHWZ and desert zones. The low-lying quadrats will be monitored in the autumn before the high flow, in the spring immediately afterwards, and in the future under the long-term monitoring program.. Topography, particle-size distribution, ground and shrub cover, species composition and basal area and dead-stem density will be monitored. Relationships between vegetation and geomorphology of those study areas lying within the GCES GIS reaches are being

interpreted through detailed GIS maps. Comparable quadrats in tributaries should continue to be monitored to provide off-river controls.

Continued searches for critical (endemic or endangered) and non-native plant species will be made in the range of dam operations within the river corridor. To date, no endangered plant species are at risk from dam operations in the Grand Canyon (Stevens and Ayers 1993, 1994). However, flooding may potentially increase the ranges of hydrochorous non-native species in this system. We will define and monitor the distribution of selected non-native species known to be expanding in this system, including *Tamarix pentandra, Alhagi camelorum, Lepidium latifolium, Saccharum ravennae*, and others identified by Stevens and Ayers (1993,1994).

Secondary Null-hypothesis 1b:

The marsh at river mile 55.5R will be used for detailed study of marsh vegetation response to sediment scour in coordination with teams studying eddy sediment transport processes. Before and after the high-flow experiment, basal area and standing crop measurements will be made along and maps of the topographic surface will be produced and analyzed to determine how high flows altered the surface.

This component will be studied by empirical measurement of velocity changes under different flow levels in relation to pre-existing vegetation at the 55.5R study site. Pre-existing and post-flood vegetation will be measured at 55.5R using the methodology established by Stevens and Ayers (1993) and described under Secondary Null-hypothesis 1a (above). Sedimentology of the new deposits, and root and stem density of remaining vegetation will be measured in relation to scour patterns of vegetation. Present hypotheses of vegetation scour include the following: vegetation is lost to bar wide turbulence of sediments, floating out vegetation.

Null hypothesis 2:

This component will be monitored on a system-wide basis using the approaches outlined in Secondary null-hypothesis 1a (above). Initial monitoring after the flood will only determine seedling establishment of invasive species. Long-term assessment of non-indigenous species post-flood colonization of this system will be part of the long-term monitoring program. As part of long-term monitoring, vegetation remapping at selected eddies at selected intervals following the flood will further augment census data. Monitoring sites will also provide information on flood-related changes in the distribution of *Lepidium latifolium, Alhagi camelorum, Saccharum ravennae* and other non-indigenous species.

Benthic Community and Organic Matter Displacement and Drift

Objectives

The objectives of this part of the study are to understand how high discharges interact with geomorphic influences (e.g., scouring of backwaters, reconfiguration of eddies and bars) to reset the distribution and abundance of algae and invertebrates within the entire river corridor, to

determine the effects of high discharges on the ecological processes within backwaters (eddy return channels), and to determine the effect of flooding on entrainment and drift of channel bed and detrital organic matter. This organic matter, found in normal drift in small amounts, may be a critical component of the food base in the heterotrophic downstream reaches of the Canyon.

Emphasis will be given to downstream transport (flux) and communition (recycling) of limnetic particulate organic matter (POM) from Lake Powell and benthic POM from the autotrophic Glen Canyon Dam - Paria segment in relation to loading of terrestrial POM by the flood wave. Emphasis on lower trophic levels of the riverine food web is based on the relatively low magnitude of the experimental flood relative to historic flows prior to closure of Glen Canyon Dam.

Justification

Regulation of flow by Glen Canyon Dam has dramatically changed the aquatic food web of the river downstream from the dam. Cold, clear and nutrient-laden water releases from Lake Powell (Stanford and Ward 1991) stimulate production of benthic algae which are fed upon by a simple consumer assemblage, dominated by midge larvae and freshwater scud (Blinn et al 1992). Midges and scud are the primary forage for fishes in the river. Bioproduction is highest in the river segment from the dam to the confluence of the Paria River, but biomass of algae and invertebrates declines dramatically downstream because the food web is impacted by high concentrations of suspended sediment that enters the river from the Paria River, Little Colorado River and other tributaries. Suspended sediment, coupled with fluctuating flows for hydropower production, prevent significant production of benthic algae through severe light limitation, reduction of solid substrate, and constant dewatering of near-shore environments where autotrophic production in unregulated rivers normally maximizes. As a consequence, the food web of the river is far less productive downstream of the clear water segment (dam to Paria); drift and benthos samples often contain few, if any, macroinvertebrates (Usher and Blinn 1990, Blinn et al. 1993). Indeed, everywhere downstream from the Paria River confluence, the Colorado River may best be characterized as being much like a glacial river, cold, turbid and unproductive.

As the Colorado River changes from an autotrophic system near the dam to a heterotrophic system downstream the composition of organic-matter drift changes (Blinn et al., 1994). The upper reaches are dominated by *Cladophora* and its epiphytes. The lower are characterized by drift from tributaries and eddies, displaced stages of substrate-dependent invertebrates and live and dead young stages of fish species.

The quantity and composition of drift may depend on discharge and associated river stage. Studies during interim flows demonstrated that there was at least a two-fold increase in drift during fluctuating discharges that attained high ebb stages of only 368m^3/s (13,000 cfs) as compared to steady discharges of 227 m^3/s (8,000 ft^3/s) (Blinn et al. 1993). High steady discharges may be expected to produce considerably more drift, at least initially. Time of year of high discharges may also affect the food base and its representation in drift because of different life stages of various aquatic organisms. For example, larval forms of some chironomid species may be common at a given time at one location, but later or elsewhere scarce following downstream drift during pupation (Blinn et al 1993).

The influences of limited bioproduction on distribution and abundance of fishes is not clear, but may contribute to observed decline of trout with distance from the dam. Numbers of indigenous minnows, including the endangered hump back chub, and suckers also are low throughout the river corridor from the dam to Lake Mead, while non-indigenous fishes are often surprisingly abundant in the turbid lower most reaches (Valdez 1993). Fish distribution and abundance may be supported to some extent by ephemeral inputs of terrestrial insects and detritus and the ability of fish to move in and out of tributaries to forage. Many may be migratory from Lake Mead. Moreover, fishes may be able to utilize low- velocity habitats (e.g., backwaters) created where large eddy systems develop. Eddies tend to entrain drifting organic matter that fishes can feed on efficiently and bioproduction of fish forage may be stimulated in backwaters by inputs of nutrient-rich ground water derived from interstitial flow through the eddy complex alluvium. However, enhanced bioproduction in backwaters, relative to the river channel, usually is negatively influenced by fluctuating flows which destabilize substratum, nutrient supply, temperatures and water clarity (Stanford, 1993).

The highly autotrophic dam tailwater (dam to Paria River) produces and exports POM which apparently serves as the primary energy source for heterotrophic processes that control bioproduction within turbid reaches downstream. Cycling of drifting particulate organic matter in the turbid reaches of the river is however likely flow dependent. Higher flows scour more POM in the tailwaters but also transport it further downstream before it can be entrained and recycled. Lower flows scour less POM in the tailwaters, but may allow more efficient entrainment and recycling in downstream food webs.

Understanding flow-mediated controls on bioproduction of riverine food webs clearly should be examined in a long term context along with geomorphic processes as determinants of flow regimes to protect and enhance canyon resources. Episodic high flows are needed to maintain geomorphic features and it is assumed that, owing to the coupling of bioproduction to its physical setting (sensu Southwood, 1977), episodic flooding is important to food web structure and function (Stanford, 1993). Base flow operations occur most of the time and have been assessed for certain food web variables (Blinn and Stevens 1994). Although, influence of flood flows on the riverine food web has not been assessed quantitatively, studies during GCES Phase I and Phase II indicate that as the dam discharge increased into the upper range of power plant capacity, sediment and organic matter became entrained (Leibfried and Blinn 1988). In many cases, organic matter drift caused by these elevated discharges included fragments of *Cladophora*, both living and dead, a result of exposure and desiccation during extended low discharge periods. This last phenomenon has been suspected to be a cause of a reduced food base for the Lees Ferry trout population, identified by the Arizona Department of Game and Fish Department as a primary reason for reduction in vigor and size of trout during research flows.

The significance of quantity and composition of organic drift relative to discharge is determined through our knowledge of the importance of the role of each component in the drift as a "loss" from one part of the riverine ecosystem or as a "resource" for other downstream components of the ecosystem. Thus, information on organic matter drift is important both on a system-wide and reach basis, the former indicating how drift from one reach or tributary might serve downstream reaches, while the latter indicating how organic matter loss and/or change in one reach might be detrimental to other aquatic components of that reach.

Benthic Communities

Null Hypothesis--

HO: Benthic biomass and community structure is sufficiently stable that it will not be significantly altered by any component of a experimental flood event.

Alternative Hypothesis--

H1: Benthic biomass and community structure will be more altered in the upper reaches below Glen Canyon Dam because different components of the experiment flood event, including rate of the rising limb, duration, and rate of decline have greater influence in these reaches.

Methods

Sampling sites for benthos will be established: (1) near Glen Canyon Dam, (2) near (upstream of) confluence of Paria River at Lees Ferry , (3) near the USGS cable way at Little Colorado River (upstream of LCR), (4) near the USGS cable way of the Grand Canyon gage, and (5) near Diamond Creek; and in eddies being studied for sediment transport.

Within 10 days prior to and after the experimental flood, standing crops of attached algae and invertebrates will be determined by dominant taxonomic group at each of the study sites. Ponar-type dredges deployed with boat mounted winch will be used in eddy sediments and a Hess sampler will be used in cobble substratum on bars and riffles. At each site, habitats created by eddies will be sampled in duplicate at a minimum of five locations along transects (i.e. two samples at each of five sampling points on each transect) through the pools previously established by Blinn et al. (1993). Three pairs of Hess samples in cobble substratum will be taken at specific points on bars associated with the eddy complex at each site also previously established by Blinn et al. (1993). These samples need to be taken at or near the lower elevation of the varial zone created by fluctuating flows on channel margins. Hence, sampling crews must be cognizant of the spatial relations of minimum flows to insure sampling can occur at or below the minimum elevation of the varial zone, which is the only habitat that can contain a stable benthic food web unaffected by desiccation.

Adult and pharate specimens will be collected with sweep nets, white and UV lights and spot samples (e.g., collection of emerging adults along the shoreline). Water temperature, dissolved oxygen, pH, specific conductance, substratum size, Secchi depth, river stage and time will also be recorded at each sampling locations. Benthos will be sorted into the following 11 biotic categories (Blinn et al. 1993): *Cladophora*, blue-green algal crust, chironomids, *Gammarus*, gastropods, oligochaetes, simuliids, lumbricids, "other" invertebrates, detritus, and miscellaneous algae and macrophytes. Numbers of organisms in each biotic category will be determined along with oven-dry (60 C) mass.

Organic Matter

Null hypothesis--

HO1: Quantity or composition of organic matter drift in the Colorado River below Glen Canyon Dam will not be significantly altered by any component of an experimental flood event.

Alternative Hypotheses:

H1: Changes in quantity and composition of organic matter drift are only related to the ascending limb of an experimental flood event, all other components of the event having little effect on organic drift.

Methods

The five sampling sites for sampling benthos will also be used for sampling POM drift, (1) near Glen Canyon Dam, (2) near (upstream of) confluence of Paria River at Lees Ferry, (3) near the USGS cable way at Little Colorado River (upstream of LCR), (4) near the USGS cable way of the Grand Canyon gage, and (5) near the USGS cable way at Diamond Creek; and at eddy locations studied for sediment transport.

Measurement of drift of coarse POM will be made with duplicate 0.5 m diameter nets (500 um mesh) deployed from boats in the middle of the channel at each cable site and within the eddies. Nets will be deployed at least 10 min to obtain samples. Timing of drift net sampling will correspond to different stages of the experimental flood event. Sampling will occur during (1) pre-event low flow period, (2) ascending limb of the event, (3) high flow period, (4) descending limb of the event, and (5) post-event low flow period. At each site samples will be collected four times per day.

Characteristics of the experimental flood, taken as part of the sediment studies, will be used for testing the hypotheses of this section. Water velocity will also be recorded at the net mouth for volumetric calculations during each collection.

Samples will be sorted in the field immediately after each sampling period into the following categories: *Gammarus lacustris*, other macroinvertebrates, detritus, *Cladophora*, and other algae/macrophytes. Densities of *G. lacustris*, chironomids, simuliids and the remaining combined macroinvertebrates will be recorded while sorting. Samples field-sorted in this way later will be oven-dried to a constant weight and converted to g m3/s.

Drift of fine POM will be collected with zooplankton nets(154 um mesh) also deployed in duplicate. These samples will be preserved with a known quantity of formalin and later examined microscopically to enumerate biota, followed by determination of oven dry weight. The main purpose of these samples is to determine the downstream distribution of zooplankton exported from Lake Powell.

Two grab samples of water associated with drift samples also will be collected and appropriately preserved to allow later determination of bacterial densities (DAPI counts, Porer and Fieg 1989). These data will provide information on densities and composition of bacteria throughout the river corridor with the expectation that bacteria become more abundant with distance downstream as autochthononus and terrestrial POM is entrained. All data will be converted to mass flux per unit time of organic carbon and assessed with respect to the length of the river corridor (e.g., position of sampling site relative to source of material drifting) and passage of the flood using gradient analysis and other multivariate approaches (e.g., multiple regression).

Fishes in the Grand Canyon

Objectives

The objectives of this part of the study are to determine any effects of the high discharge event on fish populations in Grand Canyon, and, if so, whether different life stages respond differently. Another objective is to determine how responses of the species and different life stages vary in relation to different stages of the high-discharge hydrograph.

Justification

Adult and sub-adult indigenous fishes occupying unregulated canyon-bound Arizona streams of varying sizes (mean discharges, <1.0 to 25 m^3/sec) successfully resist floods three to four orders of magnitude greater than mean discharge (Minckley and Meffe 1987). The same age-classes of non-indigenous fishes were, in contrast, significantly reduced in abundance by floods exceeding only one order of magnitude in the same systems, and often totally removed at higher discharges. The same patterns existed in regulated rivers subjected to uncontrolled releases of high-volume discharges; controlled, low-volume releases had no demonstrable effects. Larval and juvenile fishes, whether indigenous or non-indigenous, are more susceptible to high discharges (Harrell 1978, Schlosser 1985), and may be expected to suffer downstream displacement by floods, assuming no "refuge(s)" are available.

Based on these data, a proposed release of about 1,190 m^3/s (42,000 ft^3/s) into the Colorado River downstream from Glen Canyon Dam (only 3 times the mean discharge of 400 m^3/s since closure of the dam and comparable to the minimum flood-flows recorded for many years of pre-dam gaging may be predicted to have no discernible effect on distribution or abundance of adults and subadults of indigenous and non-indigenous fishes in Grand Canyon. It is possible, however, that the high-discharge event may effect changes in distribution or population sizes of larval and juvenile individuals. The question is, how can such hypotheses be tested in a large and complex system so difficult of access and resistant to effective sampling?

Hypotheses

Adult Fishes -

Null hypothesis 1—

HO1: There is no distributional response of sub-adult and adult indigenous and non-indigenous fishes to the experimental flood.

It is not possible with present technology (or databases) to determine whether flood flows will affect adult fishes, either indigenous or non-indigenous. It is possible, however, to test some ideas relative to <u>how</u> adults of indigenous fishes maintain their position in canyon-bound rivers during flood by examining their distributional responses.

Secondary null hypothesis—

HO1a: Indigenous and non-indigenous adult and sub-adult fish remain in the channel and are displaced to return as they do not resist displacement during flood. They do not seek refuge from high discharges in tributary mouths or other low velocity locations.

Secondary Alternative-hypothesis--

HA1a: Indigenous and non-indigenous adult and sub-adult fish seek refuge in tributary mouths or other low velocity locations to avoid downstream displacement by high discharge events.

Justification

This hypothesis tests the premise that populations of sub-adult and adult indigenous and non-indigenous fishes in intuitive "refuge" areas (e.g., stream mouths, which are (1) ponded, low-velocity places in the system during high water in the mainstem and (2) far more accessible to sampling than the mainstem during flood) are statistically identical before, during, and following the discharge event, and further that any expected trend (e.g., an increase in numbers of fish seeking "refuge" during the event, thus resulting in a larger population sizes, unusual species' occurrence, etc., in the presumed "refuge" area) falls outside the variance of other data, collected at the same time of year by similar (comparable) techniques in other years (other things being as equal as possible).

Methods

Sampling of tributary mouths should be immediately (1-3 days) before up-ramping begins, once during the steady flow portion of the event, and at least twice afterward (one immediately [1-3 days] after down-ramping and the second no more than 10 days later).

Execution of the "experiment" should be done by the group who has already compiled or can readily compile pre-experiment information. Distance from the dam should be considered. For example, fewer adult fishes (excluding trout) may be available to colonize the Paria River on short notice (thus "responding" to the flood by seeking "refuge") than adjacent to more downstream tributary mouths. The purpose is to seek to explain equivocal results, which certainly may obtain, on the basis of data rather than speculation. A minimum of five replicates (tributary mouths) should be sampled; 10 would be more desirable.

Hypotheses

Larval and Juvenile Fishes

Null hypothesis 2--

HO2: Distribution and abundance of larval and juvenile fish will not be affected by a high discharge event.

Alternative hypothesis 2--

HA2: Distribution and abundance of larval and juvenile fish are negatively affected by flooding as a result of up- to downstream displacement.

Justification

Displacement of larval and juvenile fish downstream during flood is based on the assumption that these life-stages are unable to disperse into "refuge" areas or otherwise resist increased current velocity during flood. Studies during GCES I and GCES II have demonstrated

that temporary pooling of water at the mouth of the Little Colorado River during daily hydropower peaks of dam discharges often created a habitat conducive to larval and juvenile fish. During the descending limb of the daily peak, water in the pool would be pulled into the mainstem carrying (or entraining) the larval and juvenile fish. In this example, the larval and juvenile fish descended from the Little Colorado River. During the high-discharge event similar pools will be available at the mouths of many tributaries but the source of larval and juvenile fish may, in most cases, be from the mainstem. The ability of these life-history stages to move into such refuges as opposed to being swept downstream will be tested.

Methods

Downstream displacement of (1) larval and (2) juvenile fishes will be studied automatically for the former by thorough analysis of pre-flood, flood, and post-flood particulate drift. A need for additional, more specific studies of potential displacement of eggs and larvae is not anticipated, but the following suggestions for this aspect of the experiment may result in other kinds of data becoming available.

(2a) One danger influencing interpretation of apparent drift of eggs and larvae is that adults may respond to the event by spawning in response to (1) stabilization of discharge for the period prior to upramping; (2) increased discharge or peaking and stabilization of flow during the event; (3) as a response to the descending limb of the hydrograph, or (4) respond to the event by spawning somewhere else than in the mainstem, with the eggs or larvae entering the mainstem in some way.

Whether or not eggs or larvae appear in drift samples will depend upon (1) whether or not eggs and larvae are present in the system (have adults spawned yet?); (2) fragility of eggs and larvae (if extremely fragile or handled roughly they may be reduced to amorphous, gelatinous masses and therefore undetected); (3) hatching time of eggs deposited during one or more of the above periods (in cold water of the mainstem, hatching time will likely exceed 10 days for any species present; it may be longer, but likely not shorter); and (4) at what point in the scenario larvae or eggs deposited other than in the mainstem (e.g., in creek mouths, which is a possibility) are entrained into the channel to become susceptible to drift netting. Sampling for eggs and larvae in tributary mouths should be done (at the same time as adults and subadults are sampled to test **Hypothesis 1**, above) in order to cover the eventuality that tributary inputs may influence mainstem drift.

Hypothesis 2 would be rejected for larval fishes if changes in larval drift (which are not attributable to one or more of the potentially confounding circumstances given above) are undetectable throughout the period of the experiment. This assumes that eggs or larvae are even present during the period of study, which they will likely be based on other years of information.

(2b) Assessment of the presence or absence of downstream displacement of juvenile fishes may be possible by exhaustive sampling (adequate to obtain statistically comparable samples) by seining along 5-10 selected sandbars or by electrofishing along 5-10 selected, talus-dominated shorelines (e.g., Valdez 1993 techniques). Pre-, during, and post-flood data can thus be placed in perspective. **Hypothesis 2** would be rejected for juvenile fishes if there are (1) no statistically significant changes in the population sizes or (2) if the post-flood pattern is other than an apparent upstream depletion and downstream accrual in population sizes. The evidence

for hypothesis support would be considered equivocal if pattern changes do not both (1) exceed variations recorded previously for the various sites or (2) statistically resemble data available for other such flooding events (e.g., the Little Colorado River flooding with apparent fish displacement in 1993).

The "experiment" should be based on pre-experimental information that will need to be readily compiled. It seems unnecessary to consider sampling for juvenile fishes upstream from the mouth of the Little Colorado River unless a strong case can be made by a potential investigator, and sampling downstream should take into consideration the possibility that juvenile fishes will (and may be detected to) possibly use "refuge" areas such as stream mouths then re-disperse to the adjacent sand bar or talus-slope habitats from a very short distance away, thus becoming reduced in abundance during the flood event and reappearing in the mainstem immediately afterward. Thus, juvenile fishes should also be carefully looked for during the stream-mouth sampling directed toward testing of **Hypothesis 1**.

Trout in Lees Ferry Reach

Objectives

The objectives of this part of the study are to determine whether a flooding event from Glen Canyon Dam will have any short-term effects on the trout population in the Lees Ferry reach of Glen Canyon.

Justification

The Lees Ferry trout fishery is an important recreational resource on the Colorado River that has been investigated by the Arizona Game and Fish Department since closure of Glen Canyon Dam. Since 1991 the Department has made quarterly electrofishing trips at 15 standard locations within the 26-km Lees Ferry reach. These electrofishing "reaches", each about 830 m long and sampled with equivalent effort, were selected to represent a cross-section of available habitat types. Since 1992 the Department has tagged each hatchery stocking with uniquely coded wire tags. Approximately 140,000 fish have been marked. It is important to use the marked fish in a before- and after-flood sampling effort to determine effects of the event. These data will be related to the ongoing data collection in the quarterly electrofishing sampling protocol.

Hypotheses

Null Hypothesis–

HO: A flooding event from Glen Canyon Dam will have no significant short-term effect on the trout population in the Lees Ferry reach.

Alternative Hypothesis–

HA: The Lees Ferry trout population will exhibit a significant reduction in all size classes as a result of a flooding event.

Methods

All stocked hatchery trout will have been wire tagged prior to the experimental flood. Electrofishing sampling of the Lees Ferry reach will be done immediately before and immediately after the flood. Electrofishing protocols in place since 1991 will be followed. For this experiment, this will include 2 trips of 5 days each to sample the 26 locations sampled during the regular quarterly electrofishing sampling.

An alternative method for sampling the trout population might be accomplished through use of the fishing guides in the Lees Ferry reach and temporary changes in catch limitations. From a week prior to the high discharge event to a week after, all limits on catch might be removed. The fishing guides will be required to report all catches, including size, weight and location. The fishing period prior to, during and after the flood experiment would be primarily a "catch and release" period but with a certain "keep" number. The guides would be required to record all catch sizes and turn in the stomachs of the trout retained, these stomachs to be analyzed by the Department for possible changes in feeding habits. Any changes in population characteristics would be determined through analysis of catch data from the fishing guides.

LAKE POWELL

Objectives

The objectives of this part of the study are to (1) assess the effect of high flows from Glen Canyon Dam on the shape and extent of the withdrawal zone in Lake Powell, (2) determine the range of water qualities potentially available for release to the Glen and Grand canyons tailwaters of the Colorado River, and (3) assess change in density structure and water quality patterns in Lake Powell during high flows and immediately after high flows from Glen Canyon Dam. These data will be used to improve upon existing models available for determining effects of different withdrawal rates through dams.

Justification

Limnological processes in Lake Powell regulate the qualities of water that pass through Glen Canyon Dam to the river downstream. Low temperature and turbidity are examples of obvious qualities controlled by the reservoir. Concentrations of dissolved salts, nutrients, organic matter, and trace elements are examples of less obvious qualities.

The fact of impoundment drives many of these controlling processes, but seasonal patterns unique to this large southwestern reservoir modify the general patterns. A major driving force in establishing the seasonally changing physical structure of lakes and reservoirs is solar radiation warming surface waters such that a density barrier to wind mixing is established. This thermal stratification is the reason that water withdrawn from the penstock elevation of 1058 m (3470 ft) MSL (50 to 70 meters below the surface of Lake Powell depending on reservoir level) is always cold. Only at low reservoir level (say, 1098 m [3600 ft] MSL) during the summer months is it presently possible to withdraw warmer water from surface layers without using the spillways. Water level must be above 1108 m (3635 ft) MSL to use the spillways.

In early April, insolation will have begun to warm the surface layers but the water mass

deeper than about 10 m will remain isothermal at the winter minimum of about 8 °C. The density profile of the water column at the approximate depths of the penstocks and by-pass tubes under this condition is controlled almost entirely by water temperature. The influence of salinity on density is slight in fresh water but may be sufficient to prevent complete mixing in this canyon-bound reservoir. The conductivity profile in the spring is thus dependent on the degree of mixing that occurred during the isothermal period in the immediately preceding winter. The removal of about 0.7 MAF in seven days as projected for this experiment has the potential to significantly restructure the near-dam depth distribution of water quality.

If the withdrawal zone is constricted, this water in motion may entrain water in excess of what can be released through the dam. This generates currents near the dam that would vertically mix water above, below, and lateral to the penstocks and river-outlet works, confounding the near-dam configuration of the withdrawal zone.

At the cessation of the flood flow the water in motion must expend its momentum by generating return-flow currents along unpredictable paths. In any case the summer stratification pattern may be established quite differently than if the high flow had not occurred.

Hypotheses

The present generation of models used by the Corps of Engineers to predict the characteristics of withdrawal zones is in hand as a software package called "SELECT" (Kennedy, pers. comm.). SELECT is a refinement of the model (Bohan and Grace, 1969) that was used to develop the early understanding of the Lake Powell withdrawal zone (Merritt and Johnson, 1977). It is unlikely that the seven-day high flow designed for this flood will be sufficient to establish the steady state defined by this model, but a trend toward it might be observed in a way that could test the prediction.

Null hypothesis 1--

HO1: Removal of a large volume of water from Lake Powell will not influence or be influenced by density profiles in the lake.

Alternative hypothesis 1--

HA 1. If the density profile is constant with depth in this vicinity the withdrawal zone will encompass a large depth range and draw water from a limited distance (less than 10 km) upstream from the dam.

Secondary hypothesis 1a--

HA1a. The water quality during the flood experiment is dependent on the pattern of vertical mixing in the near-field withdrawal zone.

Alternative hypothesis 2--

HA 2. If the density profile is changing rapidly with depth, the withdrawal zone will be confined to a thin sheet at penstock depth and extend far (50 to 100 km) upstream.

Secondary hypothesis 2a--

HA2a. The water quality during the flood experiment is dependent on the far-field pattern of longitudinal entrainment and mixing.

Secondary hypothesis 2b–

HA2b. After seven days of flow, considerable momentum could be generated in a constricted withdrawal zone, which, at the close of the high flow period, will be deflected by the dam and alter the vertical thermal and salinity pattern.

Alternative hypothesis 3–

HA 3. The release of particulate organic matter in the form of zooplankton will vary with time because of differential vertical distribution or the diel vertical migratory behavior of these animals.

Methods

The measurements required to test these hypotheses are of two kinds. Both are straightforward.

First is the mapping of the flow field before, during and after the flood. This would be done most powerfully with a broad-band acoustic- doppler current-profiler (ADCP). This is expensive instrumentation and purchase is perhaps not justified for this one-time experiment. An effort will be made to borrow one or more instruments and engage help of volunteer scientists to operate them and interpret the results. There are instruments in US Geological Survey, at the Army Corps of Engineers Waterways Experiment Station, and in the power industry, but at this time success is uncertain because of scheduling or because this is a novel application for frequency characteristics of known instruments.

The RDI high resolution ADCP can be deployed in moored or mobile configurations, with capabilities of profiling current velocities of about 10 m^3/s with a profiling range of 150 m. (Lower current velocities are possible with some sacrifice of depth resolution. Conversely, depth resolution can be improved by sacrificing precision of the lower current velocity detection limit.)

Additionally, CTD profiles will be measured at several points (1, 2, 4, and 8 km) upstream from the dam. Some aspects of the flow field can be inferred from these chemical and physical data.

Second is the measurement of changing water qualities above and immediately below the dam. Grab samples and CTD profiles will be made daily during the experimental period. These will be in Lake Powell at the outflow depths (surface elevation, 3470 ft, and 3374 ft MSL), and in Glen Canyon at the USGS cable-way. Samples will be filtered, preserved, and iced in the field for later analysis of a full suite of analytes: nutrients, major ions, trace elements and metals.

Drift nets for zooplankton will be deployed from the USGS cable-way at Glen Canyon. Triplicate 15-minute tows at three- hour intervals for 1 24-hour period before and at least 2 24-hour periods during the flood. This sampling will be part of the organic matter drift study.

Sampling for water quality and with drift nets at the USGS cable-way at Glen Canyon will be coordinated with the organic-drift sampling personnel and schedules.

CULTURAL RESOURCES

Objectives

Throughout the river corridor of Grand Canyon, locations abound that represent sacred and historical resources of both Indians of the area and modern cultures. The objective of this aspect of the experiment is to carefully monitor cultural sites within the corridor in relation to the experimental flood to insure that these locations are not altered because of the experiment, and if they are, to ascertain the specific processes contributing to their alteration.

Justification

An experimental flood as planned has the potential of disturbing elevated sediment deposits along the edges of the river corridor. Many cultural locations potentially could be disturbed by a flood of the magnitude recommended for this experiment. On the other hand, the purpose of this experiment is to demonstrate that high flows will create elevated sediment deposits, deposits that potentially could replace those eroded overtime by operations of the Glen Canyon Dam and the periodic natural floods (e.g., 1983). Concern for these resources and the need to establish sedimentary protection are important reasons for monitoring these locations as part of this experimental flood study plan. It is not expected, however, that the flood will have any significant effect on these resources.

Hypotheses

Null-Hypothesis--

HO: The experimental flood will cause some changes to the cultural resources of Grand Canyon as sediment deposits are altered in the vicinity of these resources.

Alternative Hypothesis--

HA: There will be no demonstratable changes to the cultural resources of the Grand Canyon as a result of flooding because the flows will not be sufficient to alter site dependent sediment deposits.

Methods

Evaluation of the effects of the flood experiment on the cultural resourcs of Grand Canyon will be based primarily on aerial photography and the regular monitoring program already established by agreements between the Bureau of Reclamation and the tribes under Section 106 of the National Historic Preservation Act . Selected sites near sediment and riparian study locations will have close surveillance during the flood. These sites will be considered representative of the many locations throughout the Canyon.

OTHER ENDANGERED SPECIES

There are endangered species in the Grand Canyon River corridor that have not been considered in this work plan. These include the Kanab Amber Snail and the Southwestern

Willow Fly Catcher. Both species potentially could have their habitat altered by the flood experiment. For this reason, the Bureau of Reclamation is working with the U.S. Fish and Wildlife Service to design appropriate monitoring programs that will insure close consideration of these species before, during and after the flood experiment.

LITERATURE CITED

(Incomplete)

Andrews, E. D. 1991. Sediment transport in the Colorado River basin. Pages 54-74 in Colorado River Ecology and Dam Management. Proceedings of a symposium, May 24-25, 1990, Santa Fe, New Mexico. National Academy Press.

Andrews, E.D. 1990. The Colorado River: a perspective from Lees Ferry, Arizona. Pages 304-310 in Wolman, M.G. and H.C. Riggs (eds). Surface Water Hydrology. Geological Society of America. The Geology of North America. Vol 0-1.

Armitage, P.D. 1984. Environmental changes induced by stream regulation and their on lotic macroinvertebrate communities. Pp. 139-165 in Lillehammer, A. and S.J. Saltveit (eds), Regulated rivers. Universitetsforlaget AS, Oslo, Norway.

Ayers, T.J., R.W. Scott, L.E. Stevens, K.Warren, and A.M. Phillips III. Additions to the flora of Grand Canyon National Park. Madrono (in press).

Beus, S.S., S.W. Carothers, and C.C. Avery. 1985. Topographic changes in fluvial terrace deposits used as campsite beaches along the Colorado River in Grand Canyon. J. Ariz/Nev. Acad. Sci. 20:111-120.

Blinn, D.W. and G.A. Cole. 1991. Algal and invertebrate biota in the Colorado River: comparison of pre- and post-dam conditions. Pp. 102-123 in Marzolf, G.R. (ed). Colorado River ecology and dam management. National Academy Press, Washington, D.C.

Blinn, D.W., L.E. Stevens and J.P. Shannon. 1992. The effects of Glen Canyon Dam on the aquatic food base in the Colorado River corridor in Grand Canyon, Arizona. Glen Canyon Environmental Studies Report No. II-02. Flagstaff, Az.

Blinn, D.W., L.E. Stevens, and J.P. Shannon. 1993. Interim flow effects from Glen Canyon Dam on the aquatic food base in the Colorado river in Grand Canyon National Park, Arizona: 1993 Draft Annual Report. Glen Canyon Environmental Studies.

Campbell, C.J. and W. Green. 1968. Perpetual succession of stream-channel vegetation in a semiarid region. Journal of the Arizona Academy of Sciences 5:86-98.

Carothers, S.W., S.W. Aitchison, and R.R. Johnson. 1979. Natural resources, white water

recreation, and river management alternatives on the Colorado River, Grand Canyon National Park. Proceedings of the First Conference on Scientific Research on the National Parks 1: 253-260.

Clark, J.J., E.L.Kyle and J.C. Schmidt. 1991. Mapping sediment storage changes along the Colorado River in Grand Canyon: (abstr.), kn AGU 1991 Fall Meeting Program and Abstracts: Eos 72:223.

Clover, E.U., and L. Jotter. 1944. Floristic studies in the canyon of the Colorado and its tributaries. American Midland Naturalist 32:591-642.

Connell, J.H. 1978. Diversity in tropical forests and coral reefs. Science 199:1302-1310.

Day, R.T., P.A. Keddy, J. McNeill, and T. Carleton. 1988. Fertility and disturbance gradients: a summary model for riverine marsh vegetation. Ecology: 69:1044-1054.

Dolan, R., A.D. Howard, and A. Gallenson. 1974. Man's impact on the Colorado River in Grand Canyon. American Scientist 62:393-401.

Gore, J.A. and G.E. Petts (eds.). 1989. Alternatives in regulated river management. CRC Press, Inc., Boca Raton.

Gregory, K.J. and A.M. Gurnell. 1988. Vegetation and river channel form and process. Pp. 11-42 in Viles, H.A., editor. Biogeomorphology. Blackwell.

Gregory, S.V., F.J. Swanson, W.A. McKee, and K.W. Cummins. 1991. An ecosystem perspective of riparian zones. BioScience 41:540-551.

Grime, J.P. 1979. Plant strategies and vegetation processes. Wiley, Chichester, England.

Harrell, H.L. 1978. Response of the Devil's River fish community to flooding. Copeia 1978:60-68.

Howard, A. and R. Dolan 1981. Geomorphology of the Colorado River in the Grand Canyon. J. of Geology 89:269-298.

Hupp, C.R. and W.R. Osterkamp. 1985. Bottomland vegetation along Passage Creek, Virginia, in relation to fluvial landforms. Ecology 66:670-681.

Huston, M. 1979. A general hypothesis of species diversity. American Naturalist 113:81-101.

Johnson, R.R. 1991. Historic changes in vegetation along the Colorado River in the Grand Canyon. Pp. 178-206 in Marzolf, G.R., editor. Colorado River ecology and dam management.

National Academy Press, Washington, D.C.

Kearsley, L.H., J.C. Schmidt and K. Warren. Effects of Glen Canyon Dam on Colorado River sand deposits used as campsites in Grand Canyon Nationa Park. Regulated Rivers (in press).

Kieffer, S.W. 1985. The 1983 hydraulic jump in Crystal Rapid: implications for river-running and geomorphic evolution in the Grand Canyon. J of Geology 93:385-406.

Kieffer, S.W., J.B. Graf and J.C. Schmidt. 1989. Chapter 3: Hydraulics Grand sediment transport of the Colorado River. Pages 48-66 in Elston, D.P., G.H. Billingsley and R.A. Young (eds) Geology of Grand Canyon, northern Arizona: 28th International Geological Congress Field Trip Guidebook t115/315. Washington, D.C., American Geophysical Union.

Kozlowski, T.T. Flooding and plant growth. Academic Press, Inc. Orlando, FL.

Laursen, E.M., S. Ince and J. Pollack. 1976. On sediment transport through the Grand Canyon. Pages 4-76 to 4-87 in Proceedings of the Third Federal Interagency SEdimentation Conference Water Resources Council, Sedimentation Committee.

Maddux, H.R. et al 1987. Evaluation of varied flow regimes on aquatic resources of Glen and Grand Canyons. Glen Canyon Environmental Studies. USDC, NTIS PB88-183439.

Marzolf, G.R., editor. 1991. Colorado River ecology and dam management. National Academy Press, Washington, D.C.

Minckley, W.L. & G.K.Meffe. 1987. Differential selection by flooding in stream fish communities of the arid American Southwest. Pp. 93-104, in, W.J.Matthews and D.C.Heins (eds.), Community and Evolutionary Ecology of North American Stream Fishes. Univ.Oklahoma press, Norman.

Nilsson, C. 1984. Effect of stream regulation on riparian vegetation. Pp 93-106 in Lillehammer, A. and S.J. Saltveit. Regulated rivers. Oxford Uniersity Press, New York.

Patten, D.T. 1991. Glen Canyon Environmental Studies research program: past, present and future. Pp. 239-253 in Marzolf, G.R., editor. Colorado River ecology and dam management. National Academy Press, Washington, D.C.

Phillips, B.G, A.M. Phillips III and M.A. Schmidt-Bernzott. 1987. Annotated checklist of vascular plants of Grand Canyon National Park. Grand Canyon Natural History Association Monograph No. 7. Grand Canyon, AZ.

Pickett, S.T.A. and P.S. White. 1985. The ecology of natural disturbance and patch dynamics.

Academic Press, Orlando.

Ponamperuma, F.N. 1984. Effects of flooding on soils. Pp. 10-45 in Kozlowski, T.T. Flooding and plnant growth. Academic Press, Inc. Orlando, FL.

Randle, T. J., R.I. Strand and A. Streifel. 1993. Engineering and environmental considerations of Grand Canyon sediment management. In Engineering Solutions to Environmental Challenges: Thirteenth Annual USCOLD Lecture, Chattanooga: U.S. Committee on Large Dams, Denver.

Resh, V.H., A.V. Brown, A.P. Covich, M.E. Gurtz, H.W. Li, G.W. Minshall, S.R. Reice, A.L. Sheldon, J.B. Wallace and R.C. Wissmar. 1988. The role of disturbance in stream ecology. Journal of the North American Benthological Society 7:433-455.

Rubin, D.M., J.C. Schmidt, R.A. Anima, R.E. Hunter, H. Ikeda, B.E. Jaffe, R. McDonald, J.M. Nelson, T. E. Reiss and R. Sanders. 1992. Internal structure of bars in Grand Canyon and evaluation of proposed flow alternatives for Glen Canyon Dam. U.S. Geological Survey Open-file Report, 46 pp.

Rubin, D.M., J.C. Schmidt, and J.N. Moore. 1990. Origin, structure, and evolution of a reattachment bar, Colorado River, Grand Canyon, Arizona. Journal of Sedimentary Petrology 60:982-991.

Schlosser, T.W. 1985. Flow regime, juvenile abundance, and the assemblage structure of stream fishes. Ecology 66:1484-1490.

Schmidt, J.C. 1990. Recirculating flow and sedimentation in the Colorado River in the Grand Canyon, Arizona. J. of Geology 98:709-724.

Schmidt, J.C. and J.B. Graf. 1990. Aggradation and degradation of alluvial sand deposits, 1965 to 1986, Colorado River, Grand Canyon National Park, Arizona. U.S. Geological Survey Professional Paper 1493.

Schmidt, J.C., D.M. Rubin and H. Ikeda. 1993. Flume simulation of recirculating flow and sedimentation. Water Resources Research 29:2925-2939.

Smith, W.O., C.P. Vetter, G.B. Cummings, et al., 1960. Comprehensive survey of sedimentation in Lake Mead 1948-1949. U.S. Geological Survey Professional Paper 295.

Southwood, T.R.E. 1977. Habitat, the templet for ecological strategies.

Stanford, J.A. 1993. Instream flows to assist the recovery of endangered fishes of the Upper Colorado River Basin: Review and synthesis of ecological information, issues, methods and

rationale. Report prepared for Instream Flow Subcommittee of the Recovery Implementation Program for Endangered Fish Species of the Upper Colorado River Basin and U.S. Fish and Wildlife Service, Denver, Colorado. Open File Report 130-93. 89 pp.

Stanford, J.A. and J.V. Ward. 1991. Limnology of Lake Powell and the chemistry of the Colorado River, pp. 75-101. in: Colorado River Ecology and Dam Management. Proceedings of a Symposium, May 24-25, 1991, Santa Fe, New Mexico. National Academy Press, Washington, D.C.

Sousa, W.P. 1984. The role of disturbance in natural communities. Annual Review of Ecology and Systematics 15:353 391.

Stevens, L.E. 1989. Mechanisim of riparian plant community organization and succssion in the Grand Canyon, Arizona. Northern Arizona University PhD Dissertation, Flagstaff, AZ.

Stevens, L.E. and T.J. Ayers. 1993. The impacts of Glen Canyon Dam on riparian vegetation and soil stability in the Colorado River corridor, Grand Canyon, Arizona. Final Report to the Bureau of Reclamation Glen Canyon Environmental Studies. Flagstaff, AZ.

Stevens, L.E., and G.L. Waring. 1985. The effects of prolonged flooding on the riparian plant community in Grand Canyon. Pp. 81-86 in Johnson, R.R. et al. (eds.). Riparian ecosystems and their management: reconciling conflicting uses. USDA Forest Service General Technical Report RM-120. Washington, DC.

Stevens, L.E., and G.L. Waring. 1988. Effects of post-dam flooding on riparian substrate, vegetation, and invertebrate populations in the Colorado River corridor in Grand Canyon. National Technical Information Service PB88-183488/AS, Washington, D.C.

Stevens, L.E., J.C. Schmidt, T.J. Ayers, and B.T. Brown. Geomorphic influences on fluvial marsh development along the dam-regulated Colorado River in the Grand Canyon, Arizona. Ecological Applications, in review.

Stevens, L.E., D.W. Blinn, R.A. Valdez, D.T. Patten, and D.L. Wegner. Impacts of reduced disturbance intensity on aquatic-riparian linkage: the regulated Colorado River in the Grand Canyon, Arizona. Ecological Applications, in review.

Swanson, F.J., S.M. Wondzell and G.E. Grant. 1992. Landforms, disturbance and ecotones. Pp. 304-323 in Hansen, A.J. and F. di Castri (eds.). Landscape boundaries: consequences for biotic diversity and ecological flows. Springer-Verlag, New York.

Ter Braak, C.J.F. 1992. CANOCO - a FORTRAN program for cannonical community ordination. Microcomputer Power, Ithaca, NY.

Thorp, J.H. and M.D. Delong. 1994. The riverine productivity model: an heuristic view of carbon sources and organic processing in large river ecosystems. Oikos 70:305-308.

Tilman, D. 1988. Plant strategies and the dynamics and structure of plant communities. Princeton Monographs in Population Biology 26. Princeton University Press, Princeton.

Turner, R.M. and M.M. Karpiscak. 1980. Recent vegetation changes along the Colorado River between Glen Canyon Dam and Lake Mead, Arizona. U.S. Geological Survey Professional Paper 1132, Washington, D.C.

U.S. Bureau of Reclamation. 1994. Draft Environmental Impact Statement, Operations of Glen Canyon Dam, Colorado River Storage Project. Salt Lake City, 324 pp.

Van Ness, E.H., H. Coops and M. Scheffer. 1993. EMERGO: emergent macrophytes encoded as rule governed objects. RIZA, Lelystad, NL.

Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell, and C.E. Cushing. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Science 37:130-137.

Ward, J.V. and J.A. Stanford. 1979. The ecology of regulated streams. Plenum Press, New York.

Ward, J.V. and J.A. Stanford. 1983. The serial discontinuity concept of lotic ecosystems. Pp. 29-42 in Fontaine, T.D., and S.M. Bartell, editors. Ecology of river systems. Dr. W. Junk Publishers, Dordrecht, the Netherlands.

Warren, P.L., K.L. Reichert, D.A. Mouat, B.T. Brown, and R.R. Johnson. 1982. Vegetation of Grand Canyon National park. National Park Service Cooperative Parks Studies Unit Technical Report Number 9, Tucson, AZ.

Webb, R.H., P.T. Pringle and G.R. Rink. 1989. Debris flows in tributaries of the Colorado River in Grand Canyon National Park, Arizona. U.S. Geological Survey Professional Paper 1492. 39 pp.

Wetzel, R.G.and G.E. Likens. 1979. Limnological Analysis. W.B. Saunders, Philadelphia, Pennsylvania. 357 pp.

White, P.S. 1979. Pattern, process, and natural disturbance in vegetation. Botanical Review 45: 229-299.

Wilson, R.P. 1986. Sonar patterns of Colorado River bed, Grand Canyon. In Proceedings of the Fourth Federal Interagency Sedimentation Conference, Las Vegas, March 24-27, 1986. Subcommittee on Sedimentation, Interagency Advisory Committee on Water Data. Pp. 5-133 to

5-142.

Arizona State University
Center for Environmental Studies
Box 873211
Arizona State University
Tempe, AZ 85287-3211

(602)965-2975
FAX (602) 965-8087
iacdtp@asuvm.inre.asu.edu

October 10, 1994

To: Experimental Flood Planning Team
From: Duncan Patten
Subject: Another Draft

I am attaching another draft of the flood experiment work plan. This has taken into account the input from many of you. I have not included all of your input because some of it was contradictory. I have attempted to demonstrate that the project is primarily a sediment oriented project but that sediment transport and deposition are driving factors for the ecological component of the study. I also tried to emphasize that geomorphological studies and ecological studies will be done cooperatively.

Some projects have been omitted from the earlier draft for various reasons. These include (1) lack of potential impacts because of reduction in the magnitude of the flood and little agreement on inclusion (e.g., debris flow study), (2) studies that will be more long-term monitoring than short-term flood impacts (e.g., long-term riparian recovery), (3) studies that would look at consequences of the flood although a return to fluctuating flows will make the study almost irrelevant (e.g., backwater bioproductivity). Some projects have been left in because of the political nature of doing the study.

I understand that the USGS continues to develop a much more comprehensive program than that presented in this work plan. I do not disagree with their approach, it is probably the best way to go, but I do not think it is saleable. Gathering data points for a model, or testing some new idea of river dynamics is laudable and should be funded, but probably not by the agency that is suggesting that the only reason for a flood is to build habitat (read that beaches), especially when funding is limited and there continue to be demands for funding the basic research program of GCES. The other aspect that plays a greater role than we would like is the Endangered Species Act. I am not certain we have addressed the concerns of the USFWS well enough, but we will not know until they write an opinion on our draft.

This draft along with the diagram enclosed has been sent to Rick Gold for distribution to the cooperators. It will be chewed on by their consultants.

I know you all will find some or many faults with this effort, but I believe it is an improvement. There is no question that we will need to get together again. Say October 27 or 28.

I will be in touch with most of you in the next week.

Thanks for your help and patience.

Duncan

received
10/13/94